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Cloud Physics

# Aerosol Interactions in the Marine Boundary Layer

The scientific community is taking an acute interest in marine boundary layer cloudiness since many believe that learning how these clouds form and dissipate will reveal new insights to global warming. This paper captures one segment of this ongoing research: aerosol effects on stratocumulus cloud formation. The significance of marine boundary layer clouds may be somewhat surprising: scientists estimate that one third of the earth's albedo results from stratocumulus cloudiness over the world's oceans. By studying aerosol effects on marine stratocumulus, scientists are trying to comprehend the myriad ramifications to mankind's consumption of natural resources.

Marine stratocumulus clouds share common features that are important when examining aerosol effects. Stratocumulus clouds are typically prolific on the western boundary of continents forming under a stable boundary layer inversion. Cloud-top radiative cooling generates a circulation pattern in marine stratocumulus that draws moisture up from the ocean surface into the cloud layer. The cloud droplet population in clouds over the ocean tends to be narrower and compared to continental clouds. The albedo of marine stratocumulus clouds increases when cloud condensation nuclei concentration - [CCN] - increases and is easily seen in satellite imagery of 'ship tracks'. The discovery of 'ship tracks' in the 1960's was the first observed example of aerosol effects in marine stratocumulus cloudiness.

Descriptions of a few the fundamental concepts in cloud physics will be helpful in understanding the findings of the marine boundary layer scientists. Drizzle is an important process that should be separated from other precipitation forms. Drizzle is a form of precipitation that is on the brink of being a raindrop. Drizzle is a warm cloud process in the marine boundary layer. Raindrops are defined as drops large enough to reach the ground before evaporating. By convention, the line between drizzle and rain is drawn at $r=0.1$mm. Drops larger than 0.1mm stand a good chance of reaching the ground but those near 0.1mm are distinguished as being drizzle drops (Rogers). Broken stratus regions are distinct in satellite imagery by their lack of cloudiness. The air mass in a broken stratus region is typically near saturation, unstable, drizzling and relatively free of cloud condensation nuclei (Hindman). A cloud's stability is often determined by its cloud droplet population and is sometimes referred to as its cloud colloidal stability. Clouds with populations averaging 10 microns are very likely stable and will tend to grow uniformly. Clouds become unstable and populations begin to grow asymmetrically and form precipitation if either of two events occur (Rogers):

1. droplets sizes exceed $r > 20$ microns
2. ice crystals form

Researchers are still investigating some aspects of these observations but it's enough to continue our investigation.

The following section describes the work of researchers in this field in chronological order. This is a very sensible approach, since most cloud research relies heavily on previous experiments and often extends or substantiates findings presented.

Although not the first report on fractional cloudiness in the marine boundary layer, Bruce Albrecht published a paper [September, 1989] linking low cloud condensation nuclei concentration to increased drizzle production and cloud dissipation. In a very convincing manner, Albright lines up a preponderance of evidence linking aerosols to cloud stability. He points to data indicating:

1. increases in [CCN] correspond to decreases in mean droplet size
2. increases in [CCN] correspond to decreases in drizzle production
3. increases in [CCN] correspond to increases in LWC

Data collected during the first FIRE experiment is also presented to support:

1. as droplet size increases, droplet concentration decreases
2. as drizzle frequency increases, droplet concentration decreases

He points out previous studies have already suggested:

1. low [CCN] promotes cloud drizzle
2. drizzle tends to decrease [CCN] promoting further drizzle production

Based on these findings, Albrecht proposes a mechanism of cloud dissipation where drizzle decreases cloud condensation nuclei concentration and forces additional drizzle production. Condensation warming in the cloud and evaporative cooling below the cloud create an inversion below the cloud layer. This drizzle mode eventually decouples the cloud from its moisture supply and drizzle reduces LWC until the cloud is effectively dissipated.

A team of researchers from around the United States capitalized a serendipitous encounter with a ship track by the R/V EGARBRAG III and gathered evidence that links aerosols to stable marine stratocumulus layers. The R/V EGARBRAG III gathered the data while cruising off the coast of Baja California. Researchers onboard the vessel succeeded in taking observations and direct measurements of a region of broken stratus and the merchant vessel's "ship track." Simultaneous imagery taken by a GOES satellite also provided a valuable perspective in defining a relationship between ship exhaust and cloud formation.

The analysis corroborated many of the earlier conjectures made about ship track phenomena and presented an additional theory of ship track formation. Measurements again found low cloud condensation nuclei concentrations in regions of broken stratus. Drizzle was also reported more frequently in this area and fogbows were reported - indicating an atmosphere with large cloud droplets. Measurements taken in the ship track show a rapid increase, or spike, in the cloud condensation nuclei concentration and enhanced cloudiness. Satellite and shipboard photography show enhanced vertical development in the ship track, suggesting a new mechanism for enhanced cloud production: induced vertical circulation. The authors surmise that heat released by ship exhaust and the plume wake enhance vertical mixing and bring additional cloud condensation nuclei down from above the inversion layer. The authors, Hindman, Porch, Durkee and Hudson, conclude that the data confirms Bowley's original hypothesis and propose a new way that ship tracks modify marine clouds in the layer.

In a paper by James Hudson and Paul Frisbie, data collected by the 1987 FIRE study is used to make important associations between marine stratocumulus clouds and cloud condensation nuclei. Measurements taken above, below and inside the cloud layer indicate that marine stratocumulus act as a sink for aerosol particles. The authors describe three processes at work in cloud layers:

1. nucleation scavenging of interstitial particles
2. removal of [CCN] by precipitation.
3. collision coalescence of cloud droplets and conglomeration of CCN

Vertical profiles of CCN revealed normal levels of aerosol above the cloud and reduced levels in and below. The researchers conclude that cloud scavenging plays an important role in reducing cloud condensation nuclei. Observations taken in the experiment show some time dependence to cloud droplet sizes and raise new questions about cloud droplet populations in the marine boundary layer.

Research has revealed an additional process in drizzling clouds that may force dissipation of marine stratocumulus. Modeling work done by Ackerman, Toon, and Hobbs suggests that cloud condensation nuclei depletion caused by drizzle may collapse the marine boundary layer. In their cloud model, initial conditions and aerosol production were varied to isolate CCN effects on cloud stability. Their research found that optical depth of marine stratocumulus can be reduced in a drizzling cloud to such an extent that radiative cloud-top cooling is turned off. The peak radiative cooling layer descends through the cloud as the optical depth gets smaller. This region of peak cooling forms a new stable inversion layer that drops through the base of the cloud. The descending inversion layer acts a barrier to vertical circulation and the marine boundary layer collapses. Their research also suggests that CCN sources may prevent cloud dissipation.

The last example of ongoing investigations in aerosol - stratocumulus cloud interactions was completed by researchers at the University of Washington and the Naval Postgraduate School. The authors of the study examined persistence of ship tracks in the Pacific. The authors note that "[ship tracks] provide the most direct evidence that natural clouds can be modified by pollution from anthropogenic sources." Data gathered remotely by satellite and in situ by a converted C-131 aircraft supports two processes in stable cloud formation:

1. reduced [CCN] in air parcels foster higher supersaturation and more condensation nuclei activations
2. gas to particle conversions produce cloud condensation nuclei

Again, measurements revealed the following:

1. ship tracks produce increases in condensation nuclei
2. ship tracks produce increases in cloud droplet population
3. ship tracks produce smaller cloud droplets

Measurements also revealed time dependence for CN activation in ship tracks. The dependence was evaluated using least square regression:

$$\frac{\mathrm{CCN}}{\mathrm{CN}}(\%) = 0.11*[age(\mathrm{min})] + 20.4$$

The authors conclude that both mechanisms may play a role in maintaining ship tracks as the cloud plume dilutes downstream of the exhaust source.

This anthology of marine stratocumulus research demonstrates that a great deal of progress has been made in understanding potential changes to stratocumulus clouds by aerosols. A preponderance of evidence links aerosol particles to cloud droplet populations and cloud colloidal stability. Particularly interesting relationships discussed in this paper are the positive feedback of drizzle in dissipating marine boundary layer clouds and the activation of condensation nuclei in downstream ship tracks. An authoritative answer to anthropogenic effects to the global heat budget may not be complete for years to come but the data heavily leans toward a strong link between pollution sources and enhanced boundary layer cloudiness.

References:

Albrecht, Bruce. Aerosols, Cloud Microphysics, and Fractional Cloudiness. Science. September, 1989.

Hindman, E. E., W. M. Porch, J. G. Hudson, and P. A. Durkee. "Ship-produced Cloud Lines of 13 July 1991." Atmospheric Environment. Vol 28, 1994.

Ackerman, Andrew, Owen Toon, and Peter Hobbs. "Dissipation of Marine Stratiform Clouds and Collapse of the Marine Boundary Layer Due to the Depletion of Cloud Condensation Nuclei by Clouds." Science. October, 1993.

Hudson, James and Paul Frisbie. "Cloud Condensation Nuclei Near Marine Stratus." Journal of Geophysical Research. Vol 96, November, 1991.

Ferek, Ronald, Dean Hegg, Peter Hobbs, Philip Durkee, and Kurt Nielson. "Measurements of Ship-induced Tracks in Clouds off the Washington Coast." Journal of Geophysical Reseach. Vol 113, September, 1998.

Rogers, R. R. and M. K. Yau. A Short Course in Cloud Physics. 3rd ed. Butterworth-Heinemann, 1989.